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Incorporating sheep into dryland grain production systems III. Impact on changes in soil bulk density and soil nutrient profiles

P.G. Hatfield[a,*], H.B. Goosey[a], T.M. Spezzano[a], S.L. Blodgett[b], A.W. Lenssen[c], R.W. Kott[a], C.B. Marlow[a]

[a] Department of Animal and Range Sciences, Montana State University, 230 Linfield Hall Bozeman, MT 59717, USA
[b] Department of Entomology, Montana State University, Bozeman, MT 59717, USA
[c] USDA, ARS, Agricultural Systems Research Unit, Sidney, MT 59270, USA

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Abstract

Changes in soil bulk density and soil nutrient profiles are a major concern of dryland grain producers considering grazing sheep on cereal stubble fields. Our objective was to compare burned, grazed, tilled, trampled and clipped wheat stubble fields on changes in soil bulk density and soil nutrient profiles. Treatments were evaluated in a series of three experiments using a randomized complete block design and four replications at each site. Contrast statements were used to make pre-planned comparisons among treatments. For Experiment 1, treatments were fall tilled, fall grazed, spring grazed, fall and spring combined (**Fall/Spr**) grazed, and an untreated control. Five mature ewes were confined with electric fence to a 111 m^2 plot for 24 h for fall and spring grazed plots resulting in a stocking rate of 452 sheeps d/ha. For Fall/Spr, the stocking rate was 904 sheeps d/ha. For Experiment 2, treatments were fall grazed, fall burned, fall tilled, and an untreated control. In Experiment 3, treatments were fall trampling by sheep, spring trampling by sheep, fall and spring combined (**Fall/Spr**) trampling by sheep, hand clipping to a stubble height of 4.5 cm, and an untreated control. Trampling treatments were done at the same stocking rates as grazing treatments but sheep were muzzled to prevent intake. In Experiment 1, post-treatment organic matter tended to be greater ($P = 0.09$) in the mean of the grazed treatments than control plots. In all of the experiments, change in soil bulk density, and soil nutrient profiles did not consistently differ ($P > 0.07$) among treatments in any manner that would suggest a detrimental impact of grazing sheep on small grain residue. These results indicate a strong potential for grazing sheep on grain stubble without adversely impacting soil bulk density or nutrient profiles.

Keywords: Soil bulk density; Grazing sheep; Tillage; Burning; Trampling

1. Introduction

Dryland grain producers are concerned about fallow management impacts on soil bulk density and soil nutrient profiles. Soil compaction results in excessive soil hardness, poor crop production, irregular plant growth, wet soil due to insufficient drainage, and reduced water use efficiency (Canillas and Salokhe, 2001; Radford et al., 2001). Soil properties such as texture, water content, and other factors such as environmental conditions and grazing intensities govern the degree to which compaction occurs (Mapfumo et al., 1999). Bulk density is also influenced by the content of organic matter and clay in the soil (Ball et al., 2000).

The majority of soil compaction in cropland is due to vehicular traffic (Radford et al., 2001). However,

* Corresponding author. Tel.: +1 406 994 7952; fax: +1 406 994 5589.
E-mail address: hatfield@montana.edu (P.G. Hatfield).

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without research focused on the impact of grazing on soil characteristics, many grain producers are hesitant to allow domestic grazing on grain stubble fields. The impact of a wide range of tillage, tractor, implement, and fertilization systems on soil characteristics has been investigated. Greenwood and McKenzie (2001) reviewed research on the effects of grazing pastures on soil physical properties. They concluded that, although grazing would compact soils, the magnitude was typically slight, except for recently tilled or very wet soils. The impact on soil characteristics by sheep grazing fallow in a cereal-fallow cropping systems has not been investigated. Although Holland and Detling (1990) concluded that increased plant-available nitrogen may be associated with grazing, and Drewry et al. (1999) and Murphy et al. (1995a) reported that sheep grazing in irrigated pastures had no long-term detrimental effects on soil bulk density, none of these studies are directly applicable to dryland cereal-fallow cropping systems.

With the other two articles (Hatfield et al., 2007a,b) in this series strongly indicating a potential benefit for grain producers to include sheep in fallow management, we were interested in impacts of grazing sheep on soil characteristics. Therefore, our objectives were to determine potential impacts of burning, grazing, tilling, trampling and clipping wheat stubble fields on soil bulk density and soil quality.

2. Materials and methods

Experiments measuring bulk density and soil nutrient profiles were conducted as part of a larger study (Hatfield et al., 2007a,b) at eight sites on four Montana farms. In this paper, we present the effects of sheep grazing and other management strategies on change in soil bulk density and nutrient status in fallowed fields in Montana. The experimental design was a randomized complete block design, replicated four times at each site. Individual plot size was 9 × 12.3 m.

Plots were sampled to determine soil bulk density and soil nutrient profiles prior to treatment imposition in the fall (September and October) and following completion of the treatments in the spring (May). For soil bulk density, treatment effects were determined using three compaction core samples per plot at each sampling time. A sample consisted of the volume of soil within the 91 cm^3 compaction core sampler (AMS, American Falls, ID). Samples were labeled and returned to a lab at Montana State University, dried at 105 °C for 48 h and weighed. Response variables were post-treatment soil bulk density (sampled in spring) and percent change in bulk density, which was calculated as [(ending mean–beginning mean)/beginning mean] × 100.

To determine soil nutrient profiles, three soil samples were taken from each plot at each sampling time. Soil samples were taken using a 2.5-cm diameter probe from 0–10 and 10–20 cm depths. Samples were composited within plot and depth. The 0–10 cm samples were analyzed for nitrate–nitrogen by extraction with KCl (Mulvaney, 1996), available phosphorus (Olsen-P, Kuo, 1996), available K, organic matter (Nelson and Sommers, 1996), electrical conductivity by 1:2 extract with KCl (Rhoades, 1996) and soil pH (Thomas, 1996). The 10–20 cm samples were analyzed only for nitrate–nitrogen.

A complete description of site, soils, precipitation, each of the 3 experiments, and statistical analysis are presented in Hatfield et al., 2007a). Briefly, in experiment 1, treatments were fall tilled, fall grazed, spring grazed, fall and spring combined (**Fall/Spr**) grazed, and an untreated control. For grazing treatments, five mature ewes were confined to 111 m^2 plot for 24 h for fall and spring resulting in a stocking rate of 452 sheeps d/ha. For Fall/Spr the stocking rate was 904 sheeps d/ha. For Experiment 2, treatments were fall grazed, fall burned, fall tilled, and an untreated control. In Experiment 3, treatments were fall trampling by sheep, spring trampling by sheep, fall and spring combined (Fall/Spr) trampling by sheep, stubble hand clipped to a height of 4.5 cm, and an untreated control. Trampling treatments were applied at the same stocking rates as grazing treatments but sheep were muzzled to prevent intake.

The study was conducted over a 2-year period at four locations per year. Locations were different each year. The model included effects of site, treatment, and site by treatment interaction and the contrast statements described in Hatfield et al. (2007a). The appropriate variable (i.e. initial nitrate–nitrogen for change in nitrate concentration or initial soil bulk density for change in bulk density) at the beginning of each experiment was tested in each model as a covariable and included when it was a significant ($P \leq 0.05$) source of variation.

3. Results and discussion

3.1. Experiment 1

Site by treatment interactions were detected ($P < 0.05$) for post-treatment and percent change in soil bulk density, therefore results are presented by treatment within site (Table 1). Site by treatment interactions were not detected ($P > 0.80$) for soil nutrient concentrations;

Table 1
Experiment 1: interaction[a] of site × treatment for post-treatment and change (post–pre-treatment) in soil bulk density (mg/m^3) in control[b], tilled[c] fall, spring, and fall + spring **(Fall/Spr)** grazed[d] treatments at eight sites[e] in Montana

Site	Control	Tilled	Grazed			S.E.	Control vs. grazed	Tilled vs. grazed	Fall vs. spring grazed	Fall and spring vs. Fall/Spr grazed
			Fall	Spring	Fall/Spr		*P*-value	*P*-value	*P*-value	*P*-value
Post-treatment bulk density, mg/m^3										
1	1.19	1.20	1.27	1.31	1.19	0.04	0.20	0.24	0.46	0.07
2	1.19	1.18	1.21	1.22	1.28	0.04	0.17	0.10	0.79	0.12
3	1.24	1.26	1.21	1.17	1.32	0.06	0.55	0.85	0.26	0.11
4	1.38	1.35	1.34	1.34	1.32	0.04	0.36	0.82	0.93	0.69
5	1.35	1.33	1.32	1.37	1.36	0.03	0.99	0.59	0.27	0.60
6	1.50	1.26	1.36	1.48	1.42	0.03	0.03	0.01	0.01	0.97
7	1.34	1.37	1.36	1.33	1.33	0.03	0.84	0.34	0.31	0.60
8	1.43	1.35	1.25	1.40	1.33	0.03	0.01	0.48	0.01	0.91
Change, %										
1	2.5	3.5	9.0	12.4	2.0	3.79	0.21	0.31	0.56	0.06
2	4.9	4.3	7.6	8.5	12.8	2.77	0.13	0.10	0.82	0.15
3	−2.6	−6.4	−2.2	5.5	−2.2	4.12	0.51	0.15	0.18	0.43
4	4.4	−2.7	−2.6	−0.1	−2.9	4.55	0.24	0.88	0.71	0.79
5	2.2	0.0	0.1	3.8	3.4	2.35	0.95	0.60	0.27	0.61
6	7.0	−9.1	−2.6	6.4	2.0	2.42	0.07	0.01	0.01	0.91
7	0.4	1.7	1.1	−1.5	−1.7	2.04	0.63	0.30	0.36	0.54
8	4.3	−1.3	−9.3	3.1	−3.1	2.48	0.01	0.48	0.01	0.91

[a] Site × treatment interactions were detected ($P < 0.05$).
[b] No input control.
[c] Shallow tillage (20 cm) was conducted within 72 h of fall grazing.
[d] Sheep grazed 111 m^2 plots for 24 h (Fall/Spr = 48 h); fall and spring grazed = 452 sheeps d/ha, Fall/Spr = 904 sheep d/ha.
[e] Sites located in Toole, Pondera, and Stillwater counties.

Table 2
Experiment 1: post-treatment[a] and percent change in soil nutrients in control[b], Tilled[c], fall, spring, and fall + spring **(Fall/Spr)** grazed[d] plots at eight sites[e] in Montana

	Control	Tilled	Grazed			S.E.	Control vs. grazed	Tilled vs. grazed	Fall vs. spring grazed	Fall and spring vs. Fall/Spr grazed
			Fall	Spring	Fall/Spr		*P*-value	*P*-value	*P*-value	*P*-value
Post-treatment										
K, mg/kg	473.3	467.6	473.0	494.6	468.9	12.28	0.68	0.42	0.21	0.32
EC, mmhos/cm	0.13	0.14	0.14	0.14	0.13	0.01	0.45	0.64	0.93	0.62
$N_{(0–10\,cm)}$, mg/kg	9.8	11.4	10.1	9.9	10.9	1.02	0.65	0.36	0.91	0.44
$N_{(10–20c\,m)}$, mg/kg	11.9	11.6	13.0	12.4	13.7	1.33	0.46	0.36	0.74	0.51
OM, %	2.1	2.2	2.1	2.2	2.2	0.05	0.09	0.80	0.17	0.71
P, mg/kg	29.7	30.0	30.6	34.8	30.6	1.63	0.21	0.29	0.07	0.30
pH	6.9	7.0	7.1	6.9	6.9	0.08	0.71	0.93	0.10	0.73
Change, %										
K, mg/kg	−10.3	−10.8	−8.8	−4.2	−11.0	2.40	0.38	0.29	0.17	0.13
EC, mmhos/cm	−22.7	−14.6	−22.2	−17.9	−25.5	4.92	0.88	0.20	0.54	0.37
$N_{(0–10\,cm)}$, mg/kg	−20.8	15.7	−18.0	−15.9	2.5	14.34	0.53	0.11	0.91	0.26
$N_{(10–20cm)}$, mg/kg	6.6	32.2	3.6	−5.8	41.8	15.97	0.71	0.30	0.66	0.03
OM, %	−3.8	1.0	−0.1	0.7	−0.2	2.28	0.12	0.73	0.80	0.85
P, mg/kg	5.4	11.2	10.5	26.9	11.3	7.47	0.19	0.55	0.12	0.41
pH	3.7	4.5	5.5	3.2	4.1	1.24	0.70	0.84	0.18	0.86

[a] No site × treatment interactions were detected ($P > 0.80$).
[b] No input control.
[c] Shallow tillage (20 cm) was conducted within 72 h of fall grazing.
[d] Sheep grazed 111 m^2 plots for 24 h (48 h for Fall/Spr); fall and spring grazed at 452 sheeps d/ha, Fall/Spr grazed at 904 sheeps d/ha.
[e] Sites located in Toole, Pondera, and Stillwater counties.

therefore, main effects of treatment across sites are presented (Table 2).

The contrast comparisons made of control versus grazed, tilled versus grazed, fall versus spring grazed, and fall and spring grazed versus the Fall/Spr treatment indicate no consist differences or trends among treatments (Table 1). The lack of differences, at least in the period of time the studies were conducted on each site, indicates no detrimental impact of grazing on soil bulk density. Soil bulk density values, ranged from 1.19 to 1.43 mg/m^3 in our study and thus were within the acceptable range of bulk density for cultivated clay loam soils, 0.9 to 1.5 mg/m^3 (Brady and Weil, 1999; Chancellor, 1977). The differences in bulk density found at Sites 2 and 6, although minor and probably of no production consequence, may have been due to different soil moisture levels at the sites and the fact that tillage always occurred in the fall, whereas half of the grazing treatments were in the spring. All fall-imposed treatments had the benefit of freezing and thawing of the soil over winter and early spring, which can reduce soil bulk density (Brady and Weil, 1999).

Post-treatment OM tended to be greater ($P = 0.09$) for the mean of the grazed treatments (fall, spring, and Fall/Spr) compared to control. In the grazed plots, possible the higher concentration of OM, which is less dense than soil, may have helped moderate any potential negative impact grazing may have had on soil compaction. Grazed and control treatments did not differ ($P > 0.12$) in nitrate–nitrogen, available (Olsen) phosphorus, available K, pH, or EC.

No differences were detected ($P > 0.11$) for post-treatment soil nutrients or percent change in soil nutrients when tilled was compared to the mean of the grazed treatments (Table 2). However, Soon et al. (2001) reported greater crop nitrogen uptake, a higher turnover rate of microbial biomass, and a higher concentration of nitrate–nitrogen at harvest in no till than conventional wheat tillage systems. Long-term, with grazing managed to remove only weeds and targeted amounts of stubble, we speculate that grazing may be similar or better than no-till systems in improving soil nutrient profiles.

Tillage is used by producers for several reasons, including improved soil tilth, controlling weeds, and incorporation of plant residues and other organic matter into the soil (Schjønning and Rasmussen, 2000). Roger-Estrade et al. (2001) reported tillage operations could improve soil structure of dense soils, incorporate fertilizer, and control weeds. However, tillage had several drawbacks, including direct economic costs, increased potential weed problems by bringing new seeds to the soil surface, increased mortality of soil fauna, and disruption of soil nutrient cycling (Schjønning and Rasmussen, 2000). Runoff of soil nutrients through water erosion is greater from tilled fields than non-tilled fields (Hansen et al., 2000; Planchon et al., 2000). Frequent use of the moldboard plow causes declines in soil organic carbon, decreased in soil structure and aggregation, reduced water infiltration rates, and increased soil erosion (Kettler et al., 2000). Francis et al. (1987) reported a significant densification of the soil layer just below soil plowing depth. Kosmas et al. (2001) looked at the effects of tillage-displaced soil on soil properties and wheat biomass, and reported displacement of topsoil by moldboard plowing reduced the effective soil depth and water holding capacity. In addition, the average soil loss from tillage was 24 to 1.8 metric tonnes/ha for stubble mulch (Fenster, 1997).

Holland and Detling (1990) concluded that increased plant-available nitrogen might be associated with grazing. Possibly, the higher stocking rate in the Fall/Spr plots compared to the fall and spring grazed plots was responsible for the elevated nitrate–nitrogen. We speculate that under long-term fallow grazing, soil N would be greater in grazed fallow fields than either mechanically or chemically tilled field. Many grain producers in Britain used sheep grazing to improve soil fertility (Owen and Kategile, 1984).

3.2. Experiment 2

In general, grazing, tillage, and burning treatments did not demonstrate consistent differences in soil bulk density in Experiment 2 (Table 3). The few differences that were attributed to treatment were relatively minor. A primary comparison of interest in Experiment 2 was fall burning compared to grazing. Under the conditions of our study, with a single, short duration grazing event, we conclude that grazing had no disadvantage compared to burning for influencing soil compaction.

Post-treatment soil nitrate–nitrogen in 0–10 cm depth tended to be greater ($P < 0.08$) for burned than control and for burned compared to grazed treatments (Table 4). No other differences ($P > 0.14$) were detected in post-treatment soil characteristics. Percent change in soil N at the 10–20 cm depth was positive for tilled and negative for burned plots ($P = 0.04$). No other differences were significant in percent change in soil characteristics.

Why burned plots had greater levels of surface N than either control or grazed plots yet had reduced subsurface N compared to tilled plots could result from several factors. Burning stubble results in decreased cover, allowing soils to warm more quickly during spring. Warmer soils typically have higher levels of biological

Table 3
Experiment 2: interaction[a] of site × treatment for post-treatment and change (pre–post-treatment) in soil bulk density (mg/m^3) in control[b], tilled[c], burned[d], and fall grazed[e] treatments at six sites[f] in Montana

	Control	Tilled	Burned	Grazed	S.E.	Burned vs. control P-value	Burned vs. tilled P-value	Burned vs. grazed P-value
Post-treatment bulk density, mg/m^3								
3	1.24	1.26	1.27	1.21	0.05	0.66	0.86	0.39
4	1.38	1.35	1.33	1.34	0.04	0.46	0.85	0.93
5	1.35	1.33	1.33	1.32	0.03	0.60	0.90	0.91
6	1.50	1.26	1.46	1.36	0.03	0.36	0.01	0.06
7	1.34	1.37	1.35	1.36	0.03	0.87	0.65	0.73
8	1.43	1.35	1.33	1.25	0.03	0.01	0.55	0.05
Change, %								
3	−2.6	−6.4	−2.8	−2.2	5.07	0.98	0.59	0.93
4	4.4	−2.7	2.0	−2.6	4.88	0.75	0.50	0.51
5	1.4	−2.7	−3.8	0.6	3.34	0.28	0.80	0.35
6	5.3	−10.5	2.8	−3.5	2.44	0.45	0.01	0.07
7	2.4	2.9	0.0	0.2	2.31	0.46	0.38	0.95
8	4.2	−1.7	−3.2	−9.3	2.02	0.01	0.60	0.03

[a] Site × treatment interactions were detected ($P < 0.05$).
[b] No input control.
[c] Shallow tillage (20 cm) was conducted within 72 h of fall grazing.
[d] Burning was conducted within 72 h of fall grazing.
[e] Sheep grazed 111 m^2 plots for 24 h in the fall.
[f] Sites located in Toole and Pondera counties.

Table 4
Experiment 2: post-treatment and percent change in soil nutrient concentrations[a] in control[b], tilled[c], burned[d] and fall grazed[e] plots at eight combined sites[f] in Montana

	Control	Tilled	Burned	Grazed	S.E.	Burned vs. control P-value	Burned vs. tilled P-value	Burned vs. grazed P-value
Post-treatment								
K, mg/kg	484.4	478.3	494.4	483.1	15.78	0.61	0.44	0.59
EC, mmhos/cm	0.11	0.12	0.13	0.12	0.01	0.14	0.50	0.35
$N_{(0–10\,cm)}$, mg/kg	10.6	11.8	14.6	10.4	1.77	0.05	0.26	0.08
$N_{(10–20\,cm)}$, mg/kg	13.1	10.8	12.3	12.5	1.81	0.87	0.73	0.78
OM, %	2.0	2.1	2.0	2.1	2.05	0.82	0.44	0.66
P, mg/kg	34.5	35.5	36.3	37.2	1.88	0.66	0.74	0.94
pH	6.5	6.6	6.5	6.7	0.11	0.99	0.77	0.33
Change, %								
K, mg/kg	−6.1	−7.4	−3.1	−5.7	3.10	0.38	0.31	0.61
EC, mmhos/cm	−30.9	−19.5	−21.6	−26.9	6.70	0.36	0.92	0.44
$N_{(0–10\,cm)}$, mg/kg	−16.4	26.3	7.9	−13.3	19.43	0.32	0.54	0.43
$N_{(10–20\,cm)}$, mg/kg	24.6	47.2	−3.5	6.1	19.24	0.38	0.04	0.42
OM, %	1.6	5.6	2.8	6.4	2.69	0.83	0.25	0.41
P, mg/kg	16.5	23.8	28.9	31.1	0.05	0.43	0.71	0.84
pH	3.1	4.4	3.8	5.2	1.74	0.87	0.82	0.51

[a] No site × treatment interactions were detected ($P > 0.42$).
[b] No input control.
[c] Shallow tillage (20 cm) was conducted within 72 h of fall grazing.
[d] Burning was conducted within 72 h of fall grazing.
[e] Sheep grazed 111 m^2 plots for 24 h in the fall.
[f] Sites located in Toole and Pondera counties.

activity, including elevated nitrogen mineralization and nitrification rates (Alexander, 1977). Hobbs et al. (1991) documented that nitrogen budgets in tallgrass prairie were modified by the interaction of grazing and burning. Tillage mixes organic matter, both stubble and weeds, more evenly within the tilled zone, and decomposition of organic matter and subsequent release of nitrate could have been more uniformly distributed within the tilled zone compared to burned plots (Brady and Weil, 1999).

Du Preez et al. (2001), found no evidence to suggest any difference between burning and conventional tillage on the uptake of K, P, or Zn in a semiarid Plinthosol soil. Dormaar et al. (1979) suggested that occasional burning might not have lasting harmful effects on yield. Under dryland cropping systems, straw management systems other than burning should be implemented according to Dormaar et al. (1979). Furthermore, more Dormaar et al. (1979) speculated that more fertilizer may be required when fields are burned.

3.3. Experiment 3

Site by treatment interactions were not detected ($P > 0.78$) for post-treatment bulk density, percent change in soil bulk density (Table 5), or soil nutrient concentrations (Table 6), therefore, main effects of treatment across sites are presented.

Although soil compaction and soil remolding can occur in response to trampling (Proffitt et al., 1995), no differences were detected ($P > 0.13$) in our study for post-treatment or percent change in soil bulk density for any of the contrast comparisons done for Experiment 3 (Table 5). Although sheep in our study did not affect soil compaction, Winter and Unger (2001) reported that cattle grazing on Pullman clay, irrigated wheat fields lowered yields compared to non-grazed fields. Mapfumo et al. (1999) and Worrell et al. (1992) also reported that grazing cattle in wheat fields increased soil compaction compared to a non-grazed control. Unlike cattle, Drewry et al. (1999) found high intensity (1800 sheep per ha) sheep grazing in irrigated pastures had no long-term detrimental effects on soil compaction.

Murphy et al. (1995a) compared cattle grazing with sheep grazing on smooth-stalked meadowgrass dominant white clover sward. Animals were allowed to graze pastures until a residual herbage mass of 1100 kg dry matter per ha was reached. Stocking densities were approximately 80 animal units/ha for both sheep and cattle, and they found soil compaction to be 81% greater under grazing by cattle compared to sheep. These authors speculated that the shape and small size of the hoof might actually churn and till up the soil rather than compressing

Table 5
Experiment 3: post-treatment and percent change (pre–post-treatment) in soil bulk density (mg/m^3)[a] in control[b], clipped[c], fall, spring, and fall + spring (**Fall/Spr**) trampled[d] treatments at two sites[e] in Montana

	Control	Clipped	Trample			S.E.	Control vs. trampled *P*-value	Clipped vs. trampled *P*-value	Fall vs. Spring trampled *P*-value	Fall and spring vs. Fall/Spr trampled *P*-value
			Fall	Spring	Fall/Spr					
Post-treatment bulk density, mg/m^3	1.41	1.35	1.36	1.37	1.36	0.02	0.14	0.52	0.84	0.70
Change, %	4.4	2.6	−0.9	4.3	−0.4	2.44	0.23	0.57	0.13	0.48

[a] No site × treatment interaction was detected ($P > 0.78$).
[b] No input control.
[c] Stubble clipped in the fall to a 4.5 cm stubble height; conducted within 72 h of fall trampling treatments.
[d] All sheep were muzzled while occupying a 111 m^2 plot for 24 h (Fall/Spr = 48 h); fall and spring grazed = 452 sheeps d/ha, Fall/Spr = 902 sheeps d/ha.
[e] Sites located in Toole and Pondera counties.

Table 6
Experiment 3: post-treatment and percent change in soil nutrients in control[b] clipped[c], fall, spring and fall + spring **(Fall/Spr)** trampled[d] plots at 2 sites[e] in Montana

	Control	Clipped	Trampled			SE	Control vs. Trampled *P*-value	Clipped vs. Trampled *P*-value	Fall vs. Spring trampled *P*-value	Fall and Spring vs. Fall/Spr trampled *P*-value
			Fall	Spring	Fall/Spr					
Post-treatment										
K, mg/kg	421.1	450.8	449.0	491.0	449.0	23.27	0.09	0.58	0.28	0.40
EC, mmhos/cm	0.11	0.13	0.12	0.11	0.12	0.02	0.68	0.58	0.63	0.76
$N_{(0–10\,cm)}$, mg/kg	5.2	7.7	8.3	7.9	8.3	2.51	0.46	0.91	0.58	0.64
$N_{(10–20\,cm)}$, mg/kg	4.7	12.3	4.8	9.1	11.8	4.52	0.44	0.49	0.50	0.37
OM, %	1.8	1.8	1.9	2.0	1.8	0.08	0.24	0.21	0.54	0.24
P, mg/kg	33.2	38.7	34.8	37.0	32.4	2.67	0.63	0.21	0.56	0.29
pH	6.8	6.3	6.8	6.7	6.9	0.18	0.89	0.03	0.68	0.61
Change, %										
K, mg/kg	−19.0	−12.8	−13.5	−5.6	−14.3	4.73	0.13	0.75	0.22	0.42
EC, mmhos/cm	−24.5	−18.4	−16.1	−24.5	−16.1	11.90	0.71	0.94	0.70	0.73
$N_{(0–10\,cm)}$, mg/kg	−42.2	−14.2	−36.7	−3.0	3.4	21.20	0.23	0.93	0.26	0.37
$N_{(10–20\,cm)}$, mg/kg	−43.6	166.8	−12.7	−3.6	51.8	72.39	0.49	0.23	0.93	0.49
OM, %	−9.3	−9.7	−8.2	−1.3	−8.2	3.67	0.28	0.24	0.54	0.25
P, mg/kg	3.9	24.0	12.2	13.1	2.5	12.73	0.72	0.32	0.96	0.52
Ph	4.6	−3.1	4.7	2.6	5.9	2.72	0.95	0.02	0.59	0.50

No site × treatment interaction was detected ($P > 0.78$).
[b] No input control.
[c] Entire plot was clipped in the fall to a 4.5 cm stubble height; conducted within 72 h of fall trampling treatments.
[d] All sheep were muzzled while occupying a 111 m^2 plot for 24 h (Fall/Spr = 48 h); fall and spring = 452 sheeps d/ha, Fall/Spr = 904 sheeps d/ha.
[e] Sites located in Toole and Pondera counties.

the soil. Carbon dioxide evolution from soil microbial respiration was less in the cattle grazed treatments than the sheep grazed treatments, due to less microbial activity and cycling of nutrients (Paul and Clark, 1996) in the soil where the cattle were grazed. Microbial respiration levels were inversely related to soil compaction (Murphy et al., 1995a). More vigorous plant growth was observed under sheep grazing (Murphy et al., 1995a) and was probably related to the higher levels of nutrients cycled in the sheep grazing treatment, along with the lack of soil compaction. Higher soil nutrient levels under sheep grazing may reflect a more uniform manure and urine distribution by sheep compared to cattle (Murphy et al., 1995a).

4. Conclusion

Under the conditions of our study, sheep can be incorporated into fallow management systems without negatively impacting soil bulk density or soil nutrient profiles. Long-term grazing of fallow ground may have the added benefit of increasing available nitrogen and OM. However, additional research must be done to determine optimum stocking rate, season of grazing, and environmental conditions, particularly soil moisture, to determine when grazing should occur without negatively impacting soil bulk density.

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